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Physical Collection Efficiency of Filter Materials for Bacteria and Viruses

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The purpose of this study was to determine the physical collection efficiency of commercially available filters for collecting airborne bacteria, viruses, and other particles in the 10–900 nm (nanometer) size range. Laboratory experiments with various polytetrafluoroethylene (PTFE), polycarbonate (PC) and gelatin filters in conjunction with Button™ Inhalable samplers and three-piece cassettes were undertaken. Both biological and non-biological test aerosols were used: *Bacillus atrophaeus*, MS2, polystyrene latex (PSL), and sodium chloride (NaCl). The *B.atrophaeus* endospores had an aerodynamic diameter of 900 nm, whereas MS2 virion particles ranged from 10 to 80 nm. Monodisperse 350 nm PSL particles were used as this size was believed to have the lowest filtration efficiency. NaCl solution (1% weight by volume) was used to create a polydisperse aerosol in the 10–600 nm range. The physical collection efficiency was determined by measuring particle concentrations size-selectively upstream and downstream of the filters. The PTFE and gelatin filters showed excellent collection efficiency (>93%) for all of the test particles. The PC filters showed lower collection efficiency for small particles especially <100 nm. Among the tested filters, the lowest collection efficiencies, 49 and 22%, were observed for 1 and 3-μm pore size PC filters at the particle sizes of 47 and 63 nm, respectively. The results indicate that the effect of filter material is more significant for the size range of single virions than for bacteria. The effect of filter loading was examined by exposing filters to mixtures of PSL particles, which aimed at mimicking typical indoor dust levels and size distributions. A 4-h loading did not cause significant change in the physical collection efficiency of the tested filters.

Keywords: bacteriophages; collection efficiency; endospores; gelatin; polycarbonate; polytetrafluoroethylene

INTRODUCTION

Concern over airborne dissemination of viral particles such as the coronavirus, influenza virus and bioterrorism agents as well as the growing use of engineered nanoparticles have increased the need for additional environmental sampling techniques, especially for the nano-scale particle size range. Nanoscale particles have sizes <100 nm (Oberdörster *et al*., 2005). Viruses range in size from 20 to 200 nm and can be found in droplet nuclei or attached to other airborne particles (Reponen *et al*., 2001). Viruses in the *Orthomyxoviridae* family include those associated with influenza such as the Avian flu virus and range in size from 80 to 120 nm (Mandell *et al*., 2005). It is estimated that globally ~5% of all adults and 20% of all children develop symptomatic influenza infections each year (Nicholson *et al*., 2003). It is a costly disease that results in much human suffering as well as economic impact in terms of lost time and medical expenses. Viruses in the *Coronaviridae* family, which includes the virus linked to severe acute respiratory syndrome (SARS), range in size from 80 to 150 nm (Mandell *et al*., 2005). There is also much interest in developing environmental sampling techniques for bioterrorism agents including bacterial agents such as *Bacillus anthracis* (anthrax), *Yersinia pestis* (plague) and *Francisella tularensis* (tularemia), and viral agents including variola major (smallpox)

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and filoviruses and arenaviruses (viral hemorrhagic fevers), some of which are found in the smaller particle ranges (CDC, 2006).

Techniques that have been used traditionally for the collection of bioaerosols include centrifugal scrubbing, electrostatic precipitation, filtration, liquid impingement and impaction (Otten and Burge, 1999; Sattar and Ijaz, 2002). One limiting factor for traditional bioaerosol sampling has been the use of culturable count as a measure of exposure. The development of real-time quantitative polymerase chain reaction (Q-PCR) techniques, which do not depend on culturability, allows for the detection of microorganisms of interest with a short analysis time. This has led to the possibility of conducting longer term air sampling and the evaluation of individual exposures using personal breathing zone filter sampling instead of estimates based on short-term area monitoring.

Some bioaerosol collection techniques have been studied in great detail. Koller and Rotter looked at several issues concerning the use of gelatin filters for collecting airborne bacteria (Koller and Rotter, 1974). They found that the gelatin filters had a collection efficiency of greater than 99.95% for particles between 0.5 and 3.0 μm in size. Jaschhof used the gelatin filter to collect laboratory-generated T1 phage and influenza A virus particles (Jaschhof, 1992). He found a retention rate of 99.76% for the T1 aerosol and was able to culture influenza A virus collected during air monitoring in the room of a patient with Influenza Type A.

Myatt *et al*. (2003) used 2.0-μm pore size polytetrafluoroethylene (PTFE) filters with cassette samplers to collect airborne rhinovirus. Utilizing a reverse transcriptase polymerase chain reaction (RT–PCR), they were able to detect virus on the filter with a sampling time of 40 h. Booth *et al*. (2005) examined several different monitoring techniques to determine if SARS coronavirus could be detected in environmental samples collected in Toronto hospitals. Using a slit sampler and a PCR technique, the investigators obtained two positive air samples from a room with a recovering SARS patient. Wet swab sampling yielded positive results for commonly touched surfaces, including a bed-side table, remote control, and medication refrigerator door. At the same time, traditional air sampling with PTFE filters did not yield any results above the detection limit. It should be noted that no information was provided about extraction techniques while extraction has been shown to affect the filter sample data in a major way (Booth *et al*., 2005, Burton *et al*., 2005). Tseng and Li (2005a) investigated the collection efficiency in terms of viability for four different bacteriophages with four different samplers. They found that gelatin filter samplers, Andersen impactor samplers, and impingers were more suitable for the collection of viral particles than the sampler equipped with nucleopore (membrane) filters. Alternative sampling methodologies have also been developed, e.g. a new personal bioaerosol sampler that allows collecting bioaerosol particles through porous media immersed in a collection fluid (Agranovski *et al*., 2004 a,b). The collection fluid can then be used in various analyses.

As described above, filter sampling appears to be a promising method for sampling of viruses and bacteria. There is lack of information, however, on the collection characteristics of commonly used filters for bioaerosol sampling for the smaller bacteria and viral particles. The objective of this study was to determine the physical collection efficiency of PTFE, gelatin and polycarbonate (PC) filters for biological and non-biological particles in the nanometer range; to determine if the mass and particle size distribution found in household dust could be recreated in the laboratory using polystyrene latex (PSL) particles; and to examine the effect that loading has on physical collection efficiency for nanometer-sized particles.

MATERIALS AND METHODS

Test filters

The following commercially available filters were tested for this study: Sartorius gelatin filters with 3-μm pore size, GE Osmonics, Inc. PC filters with 0.4, 1 and 3-μm pore sizes, BHA Technologies PTFE with 0.3-μm pore size preloaded in three-part 37-mm plastic cassettes, Pall PTFE filters with 0.5-μm pore size, Zefon Corporation PTFE filters with 1-μm pore size, and Fluoropore PTFE filters with 3-μm pore size. These filters have been used successfully for bioaerosol sampling in previous studies (Willeke and Macher, 1999; Wang *et al*., 2001; CDC, 2004; Burton *et al*., 2005; Hung *et al*., 2005). Filter characteristics are presented in Table I.

Laboratory setup

The laboratory chamber system was set-up in a Biosafety Level II cabinet (SterilchemGARD; Baker Co., Sanford, ME, USA). A diagram of the experimental setup is shown in Fig. 1. The set-up is similar to the one used by Wang *et al*. (2001) and Burton *et al*. (2005). A 6-jet Collison-type air-jet nebulizer (BGI Inc., Waltham, MA, USA) was used to generate aerosols at 12 liters per minute (l.p.m.). The nebulizer solutions were vortexed for 5 min before each experiment. The generated aerosol was mixed with high efficiency particulate air (HEPA) filtered laboratory air at 30 l.p.m. The mixture passed through an electrostatic charge neutralizer (TSI Aerosol Neutralizer Model 3012, TSI Inc.,

Table 1. Characteristics of tested filters

Filter manufacturer	Material	Filter diameter (mm)	Pore size (μm)	Thickness (μm)
Sartorius (obtained from SKC Inc., Eighty-Four, Pennsylvania)	Gelatin membrane	25	3	250
GE Osmonics, Inc., Minnetonka, MN, USA	PC^	25	0.4	10
GE Osmonics, Inc., Minnetonka, MN, USA	PC^	25	1	11
GE Osmonics, Inc., Minnetonka, MN, USA	PC^	25	3	9
BHA Technologies Kansas City, Missouri (obtained from SKC Inc.)	PTFE* with back-up pad	37	0.3	38
Pall (obtained from SKC Inc.)	PTFE* with laminated PTFE support	25	0.5	178
Zefon Corporation (obtained from SKC Inc.)	Zefluor™ PTFE*	25	1.0	165
Millipore Corporation, Bedford, MA, USA	Fluoropore (PTFE*) filters with back-up pad	25	3.0	150

^PC = Poretics Polycarbonate membrane.
*PTFE = Polytetrafluoroethylene.

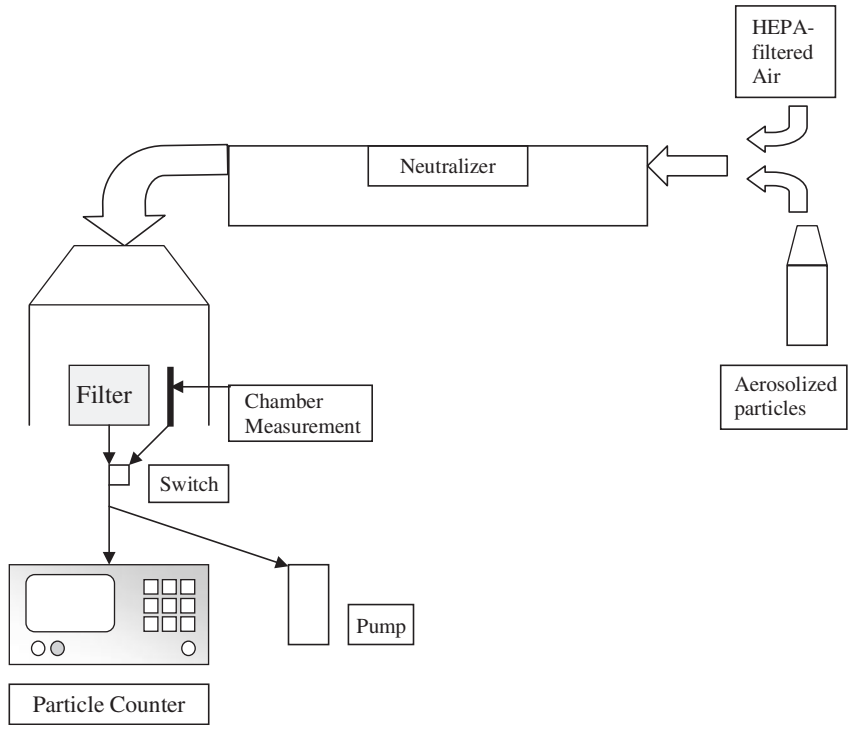

Fig. 1. Experimental set-up.

Shoreview, MN, USA) before entering the bioaerosol chamber. The experiments were conducted at ambient laboratory temperature and humidity.

Seven of the filters had a diameter of 25-mm and were used in conjunction with the SKC Button™ Inhalable Aerosol Sampler (SKC Inc., Eighty-Four, PA, USA) operated at a flow rate of 4 l.p.m. provided by an SKC Universal sampling pump (Model 224). The Button Sampler was chosen for this study since it can be used in a stationary as well as personal mode and its sampling efficiency closely follows the ACGIH/ISO inhalability curve at 4 l.p.m. (Aizenberg *et al*., 2000). The 0.3-μm pore size PTFE filters preloaded in 37-mm cassettes were also used with the SKC Universal sampling pumps but at a lower flow rate of 2 l.p.m. because that is the manufacturer's recommended flow rate. A radioactive neutralizer was used when filters were loaded into the Button Sampler to neutralize electrostatic charges. The volumetric flow rate for each sampler was pre- and post-calibrated after each laboratory run using a mini-Buck calibrator (A.P. Buck, Inc., Orlando,

FL, USA). The filters were placed inside the chamber as shown in Fig. 1.

Pressure drop measurements

Pressure drop measurements were performed with a Magnehelic® gauge (range: 0–80″ water) to determine the air resistance through the filter and sampler (Model 2080, Dwyer Instruments, Michigan City, IN, USA). Measurements for each type of filter/sampler combination were repeated using three different filters. A GAST Model 1532 rotary vane pump (Gast Manufacturing, Inc., Benton Harbor, MI, USA) was used with the 0.4 μm PC filters to achieve a consistent flow rate of 4 l.p.m. in order to obtain an accurate pressure drop measurement. The pressure drop measurements were conducted independently from the chamber experiments.

Test particles

Bacillus atrophaeus endospores were selected to represent bacteria. It is frequently used as a simulant for *Bacillus anthracis* (Burke *et al*., 2004). In 2000, the U.S. Army Edgewood Laboratories, Aberdeen Proving Ground, Maryland, provided the *B.atrophaeus* endospores [*Bacillus subtilis* subsp. *niger*, also known as *Bacillus globigii* (BG)] to the University of Cincinnati, Department of Environmental Health, Center for Health Related Aerosol Studies. The endospores have an aerodynamic diameter of ~0.9 μm (Wang *et al*., 2001). The *B.atrophaeus* endospores were washed by centrifugation thrice in sterile deionized water at 7000 r.p.m. as described by Wang and associates (Wang *et al*., 2001).

The tests were also conducted with MS2, a small RNA virus with an aerodynamic diameter of ~28 nm (Hogan *et al*., 2004). This is a bacteriophage that infects only male *Escherichia coli* bacteria (Fiers 1967; Valegard *et al*., 1990; Golmohammadi *et al*., 1993). The small size and simple structure of MS2 virions, their single-stranded RNA genome, as well as harmlessness to humans, animals, plants and other higher organisms have made MS2 particularly useful in simulating RNA viruses such as Ebola, Marburg and the equine encephalitis alphaviruses (O'Connell *et al*., 2006). In addition, MS2 bacteriophages have previously been used a surrogate for poliovirus and many other enteric viruses due to similarity of their characteristics. Several investigators utilized MS2 as a simulant of pathogenic viral strains (Belgrader *et al*., 1998; Alvarez *et al*., 2000; Shin and Sobsey, 2003; Thomas *et al*., 2004; Tseng and Li, 2005b). The MS2 bacteriophage stock solution was prepared from a freeze-dried phage stock vial (ATCC 15597-B1) by adding 9 ml of Luria–Bertani broth, which had been made using ultra-filtered deionized water. The resulting suspension was serially diluted and the final suspension resulted in 10^8 to 10^9 plaque-forming units of MS2 per milliliter of solution.

Monodisperse 0.35-μm PSL particles (Bangs Laboratory Inc., Fishers, IN, USA) were used in the physical collection efficiency measurements to represent the 0.3-μm particle size, which is believed to be the most penetrating through filters (CDC/NIOSH, 1996). One-tenth of a milliliter of re-constituted PSL particles were mixed with 50 ml of sterilized, deionized water to create stock solutions In order to determine a typical concentration and particle size distribution in indoor air to use for the loading experiment, aerosol measurements were carried out for 23 h with the OPC in a home that was part of a larger indoor air quality study (Lee *et al*., 2006a). Then, three separate PSL test mixtures were created using aliquots of 0.35, 0.54, 0.69, 0.61, 1.08, 2.43 and 5.05-μm stock solutions. The comparison of the particle size distributions of the field-measured indoor aerosol and the laboratory-generated PSL mixtures (with fractions from 0.35 to 5.05 μm) is presented in Fig. 2 as a numeric percentage. This figure shows that the field-measured levels can be reproduced in the laboratory using a mixture of monodisperse PSL particles of different sizes. The second PSL test solution showed a higher percentage of 0.5-μm particles which may be a result of incomplete mixing or clumping in the Collison nebulizer.

Sodium chloride (NaCl), which was also used as a challenge aerosol, was aerosolized from a 1% weight by volume (w/v) solution. It formed a log-normal particle size distribution in a range of 10–600 nm with the number concentration peak of 20–40 nm. The size range of NaCl aerosol included MS2 virions as well as 0.35 μm PSL particles.

Physical collection efficiency

The physical collection efficiency (E_{pce}) for the filters was determined by measuring the particle concentration upstream (C_{up}) and downstream (C_{down}) of the filter sampler. When testing with *B.atrophaeus* and 0.35-μm PSL particles, the real-time particle size resolve measurements were performed with an optical particle counter (OPC; Grimm Model 1.108, Grimm Technologies Inc., Douglasville, GA, USA), which sorts particles in 15 channels in the size range from 0.3 to >20 μm. For the *B.atrophaeus* endospores, all particles >0.65 and <2.0 μm were used to calculate initial concentrations to include any agglomerates that might have occurred (Burton *et al*., 2005). For the 0.35-μm PSL particles, the particles that were detected in the channel >0.3 and <0.4 μm were used for the calculations. When testing with smaller particles, including MS2 virus and NaCl, we used a Wide-range Particle Spectrometer (WPS™; Model 1000XP, configuration A, MSP Corporation, Shoreview, MN, USA). With

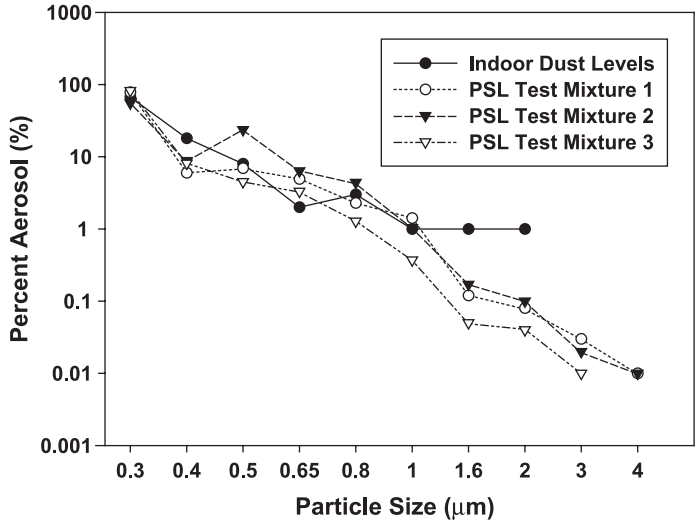

Fig. 2. Comparison of laboratory-generated PSL mixture to filed-measured indoor aerosols based on number of particles

three devices built in [the condensation particle counter (CPC), differential mobility analyzer (DMA), and light particle spectrometer (LPS)], this instrument size-selectively measures particles starting from 10 nm. The CPC and DMA measure from 10 to 500 nm (up to 96 channels) and the LPS covers particles from 350 to 10 000 nm (24 channels). The CPC and DMA were set to collect measurements in 48 channels for this study. The particle diameter range of 10–80 nm was used for the MS2 virions (Bałazy *et al*., 2006).

In each test, once the C_{up} was determined, a directional switch was used on the sampling line to measure C_{down} (Jankowska *et al*., 2000). A typical sampling time was 3 min with each filter undergoing three consecutive C_{up} and C_{down} measurements. Three different filters were used for each series of experiments and the results were averaged to determine the E_{pce}. The instrument reading during the first minute was always omitted to eliminate confounding of any material that might be left in the sampling tube.

The E_{pce} was calculated as follows:

$$E_{pce}=\left[1-\left(C_{down}/C_{up}\right)\right]\times 100\% \qquad (1)$$

Loading experiment

Loading experiments were performed to investigate if the collection efficiency of filters increases after collecting a specific amount of particles on these filters. The 4-h loading experiments were conducted using 0.3-μm pore size PTFE, 1-μm pore size PC and 3-μm pore size PTFE filters. One test PSL mixture was used for each set of filters to mimic the observed concentration and size distribution of indoor air particles.. These filters were selected for the loading tests because they showed the highest physical collection efficiency in conjunction with a pressure drop suitable for personal (breathing zone) samples. Three identical filters were loaded for each filter type. The filters were equilibrated for 7 days under control temperature and relative humidity conditions before weighing on a Mettler balance (Mettler-Toledo AT20, Mettler-Toledo, Inc., Columbus, OH, USA) before and after loading.

The E_{pce} was determined for each filter before loading using 0.35-μm PSL particles and after loading ($E_{pce\text{-}loaded}$) using 0.35-μm PSL and MS2 particles. The E_{pce} before loading measurements for the MS2 bacteriophage aerosol was determined using a separate set of identical filters to avoid additional loading of the set of filters used for loading.

Data analysis

Data analysis was performed using the SAS statistical package version 9.1 (SAS Institute, Inc., Cary, NC, USA). Paired *t*-tests were performed to compare the average E_{pce} (before) and $E_{pce\text{-}loaded}$ (after filter loading) for 0.35-μm PSL particles and MS2 bacteriophages. A one-way ANOVA was used to compare E_{pce}-values obtained with different filter types for each particle type. Multiple comparisons of the means were conducted using the Scheffé procedure as the most conservative analysis. A significance level of 0.05 was used for all statistical tests.

RESULTS AND DISCUSSION

Pressure drop measurements

The pressure drop values through the tested filter loaded in the Button Sampler or three-piece cassette are presented in Table 2. They range from 0.3 kPa for the 0.3-μm pore size PTFE filters to

Table 2. Measured pressure drop values for tested filters with samplers[a]

Filter type	Pressure (kPa)	Pressure (inches of H_2O)
0.4-μm PC[b]	15.2	61
1-μm PC[c]	5.7	23
3-μm PC	0.9	3.5
0.3-μm PTFE[c]	0.3	1
0.5-μm PTFE	8.1	32.5
1-μm PTFE	2.0	8
3-μm PTFE[c]	1.0	4
3-μm Gelatin	2.9	11.8

[a]Measurements were conducted using three different filters in conjunction with the button inhalable aerosol sampler at a flow rate of 4 l.p.m. with the exception of the 0.3-μm PTFE filters which used a three-piece 37-mm cassettes at 2 l.p.m.
[b]Used Gast pump to hold flow at 4 l.p.m.
[c]Used in loading experiments.

15.2 kPa for 0.4-μm pore size PC filters. Due to the high-pressure drop observed for 0.4-μm pore size PC at the 4 l.p.m. flow rate, this filter was not used in further testing. The 0.5-μm pore size PTFE filters also showed a high-pressure drop at 4 l.p.m., which occasionally caused pump failure during sampling. When the collection filters are used with the button sampler, the overall pressure drop can be reduced by replacing the manufacturer-provided metal filter support with an autoclavable metal mesh support as described by Lee and associates (Lee *et al*., 2006b).

Physical collection efficiency

Figure 3 presents the collection efficiencies obtained for the three test aerosols. For the airborne *B.atrophaeus*, the tests filters showed an average E_{pce} of 94% or higher. The 1-μm PTFE filter showed a statistically significantly lower E_{pce} (average 94%) when compared to the other filters. This information, however, could not be verified by additional experiments since this filter is no longer manufactured and additional filters could not be obtained. The collection of 0.35-μm PSL particles on the 3-μm pore size PC filters (average 69%) was significantly less efficient than that obtained with the other filters. For the MS2 virions, the 1- and 3-μm pore size PC filters had E_{pces} = 68 and 27%, respectively. These were statistically significantly lower than the collection efficiencies obtained for the PTFE and gelatin filters, which were >96%. Furthermore, the collection efficiency of the 3-μm PC filter was the lowest among the tested filters. The high collection efficiency for the gelatin filters for the MS2 virions agrees with the results of prior investigations (Koller and Rotter, 1974; Jaschhof, 1992).

Sodium chloride challenge aerosol

Figure 4 presents the particle size selective data on the collection efficiency of the 1- and 3-μm pore size PC filters and 0.3- and 3-μm pore size PTFE filters challenged with NaCl particles. The minimum E_{pces} for the 1- and 3-μm pore size PC were observed at the particle average diameter of 47 and 63 μm, respectively. The respective E_{pces} values were 49 and 22%. In contrast, the 0.3- and 3-μm pore size PTFE filters showed minimum E_{pces} of 99.7 and 98.4%, respectively. The data obtained with the NaCl particles is in agreement with those obtained with PSL particles of 0.35 μm and MS2 virions measured within a size range of 10–80 nm, (see Fig. 1). The low E_{pce} for the PC filters also agrees with the reported performance of PC filters since the 1980s. Hinds and Liu and associates reported that minimum filter efficiencies for membrane filters were at ~50 nm, which agrees with the data shown in Fig. 3 (Hinds 1999; Liu, 1983). In our tests, we observed that when loading and unloading the PC filters in the Button Samplers it was important to ensure that the filters were not wrinkled. Smith *et al*. (1993) noted difficulty with PC filters in terms of static charges and problems with folding and wrinkling during filter loading. It should be noted that previous studies have found that gelatin filters dried out over time and were of limited use for long-term sampling (Burton *et al*., 2005, Tseng and Li, 2005a).

Effects of filter loading

The comparison of the particle size distributions of the field-measured indoor aerosol and the laboratory-generated PSL mixture (with fractions from 0.35 to 5.05 μm) is presented in Fig. 2. This figure shows that the field-measured levels can be reproduced in the laboratory using a mixture of monodisperse PSL particles of different sizes. In order to see if this was reproducible, three separate mixtures using the same concentration of PSL particles of the different sizes were created and used in the loading experiments (Fig. 2).

When 1-μm pore size PC filters, 0.3-μm pore size PTFE filters and 3-μm pore size PTFE filters were loaded for 4 h with PSL particles, the average tared filter weights were 56 ± 7, 45 ± 10 and 47 ± 8 μg, respectively, corresponding to average airborne concentrations of 58 ± 7.3, 93 ± 22 and 49 ± 8.3 μg m^{-3}. These concentration levels are comparable to the average indoor dust concentrations (geometric mean: 27.56 ± 89.37 μg m^{-3}) determined previously during a four-season study in NC, USA (Wallace *et al*., 2006).

Figure 5 presents the physical collection efficiency of three filters before (E_{pce}) and after ($E_{pce\text{-}loaded}$) particle loading as measured with

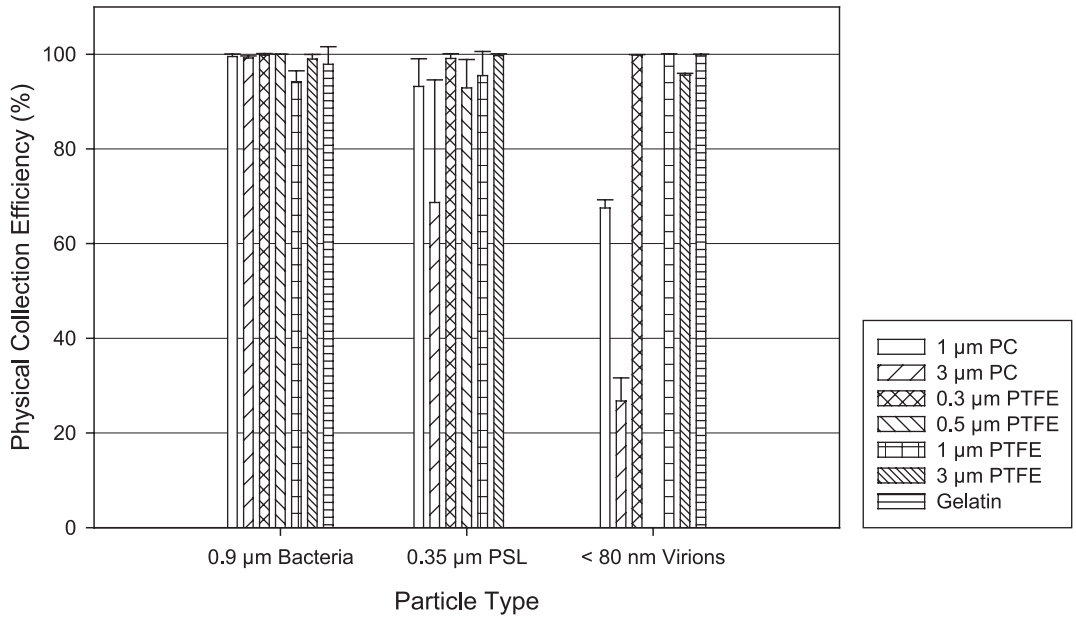

Fig. 3. Physical collection efficiency of different filters for three challenge aerosols. Note: No result was obtained with the 0.5-µm PTFE filter challenged with virions due to pressure drop/pump failure. Gelatin filters were not tested with the 0.35 PSL particles (the PCE was assumed to be ~100%). The bars and error bars represent the mean values and the standard deviations, respectively (n = 3).

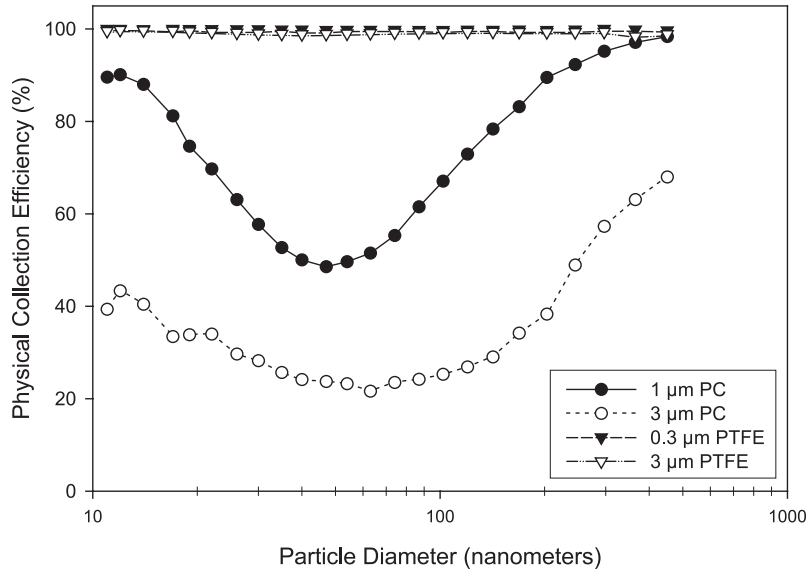

Fig. 4. Physical collection efficiency of filters challenged with NaCl particles aerosolized from a 1% (w/v) suspension as a function of the particle diameter.

0.35-µm PSL particles and MS2 virions. The collection efficiencies obtained for the pre- and post-loading for both particle types are very similar to those presented in Fig. 3. Similar to E_{pce}, the $E_{pce\text{-}loaded}$ was higher for the 0.35-µm PSL particles (>90%) than for the MS2 particles (>67%) when tested with 1-µm pore size PC filters. The 0.3-µm pore size PTFE filters exhibited high $E_{pces\text{-}loaded}$ (>99%) with both challenge aerosols. The 3-µm pore size PTFE filters showed $E_{pce\text{-}loaded}$ of >99% for the 0.35 µm PSL particles and >96% for the MS2. The PTFE filters had much higher $E_{pce\text{-}loaded}$ for the MS2 particles than the 1-µm pore size PC which is consistent with the data collected for unloaded filters. The small increase in $E_{pce\text{-}loaded}$ that was observed for the majority of the filters was anticipated. Paired t-tests, however, showed that the collection efficiencies for loaded and unloaded filters were not statistically significantly different.

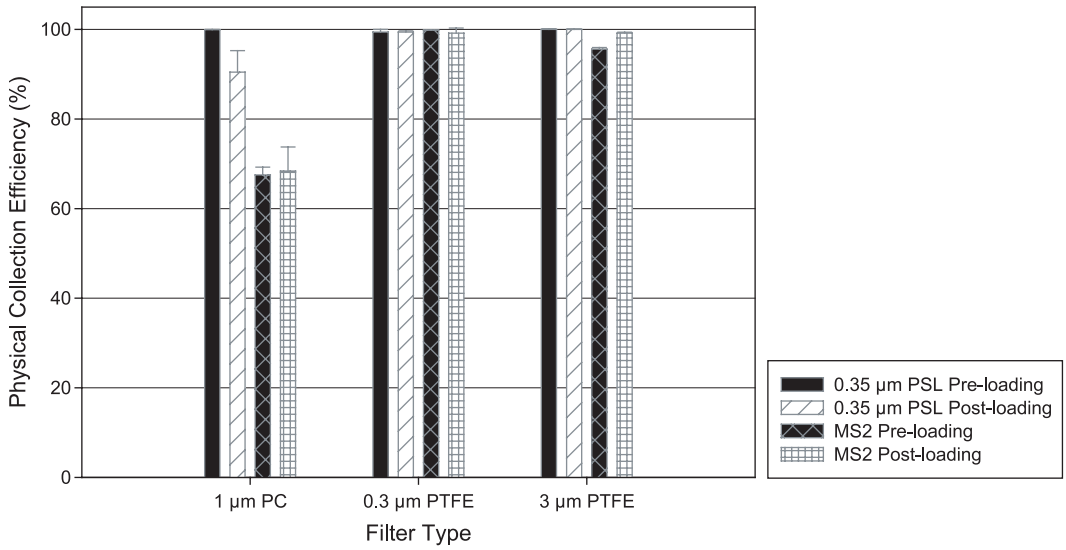

Fig. 5. Physical collection efficiency measured with 0.35-µm PSL and MS2 virions before and after loading with PSL test mixture particles. Pre-loading measurements with MS2 virions were conducted with a different set of identical filters. The bars and error bars represent the mean values and the standard deviations, respectively (n = 3).

CONCLUSIONS

The PTFE filters were found to be efficient for collecting submicrometer and nano-scale aerosol particles, including bacteria and viruses. The 0.3-µm PTFE filter used with the 37-mm three-piece cassette exhibited the lowest pressure drop and highest physical collection efficiency for *B.atrophaeus* and MS2 particles. The other PTFE filters also showed very good physical collection efficiencies across the size range of 10–900 nm with relatively low pressure drop. PTFE filters were found to have good recovery of aerosolized bacteria when used in button samplers (Burton *et al*., 2005). Additional work, however, needs to be conducted to investigate the recovery efficiency for smaller particles from the PTFE filters. The tested gelatin filter also had good physical collection efficiency, but may not be suitable for long-term sampling due to potential drying out (Burton *et al*., 2005, Tseng and Li, 2005a). The PC filters made of a thin layer of material appear to have little internal capture capability when compared to the fibrous membrane filters in the nano-scale particle size range. At the same time, the PC filters exhibited acceptable E_{pce} with the *B.atrophaeus* bacteria (the largest aerosol particles tested in this study). The findings suggest that the PTFE filters are the best option among the tested ones for long-term personal sampling of nano-scale particles and virions in terms of collection efficiency. Several of the tested filters were found to be equally appropriate for the collection of bacteria including the 1-µm PC, 0.3-µm PTFE and 3-µm PTFE filters.

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